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COUNTERCLOCKWISE MAGNETIC FIELDS IN THE NORMA SPIRAL ARM

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ABSTRACT

Pulsars provide unique probes of the large-scale interstellar magnetic field in the Galactic disk. Up to now, the limited Galactic distribution of the known pulsar population has restricted these investigations to within a few kiloparsec of the Sun. The Parkes multibeam pulsar survey has discovered many more-distant pulsars which enables us for the first time to explore the magnetic field in most of the nearby half of the Galactic disk. Here we report the detection of counterclockwise magnetic fields in the Norma spiral arm using pulsar rotation measures. The fields are coherent in direction over a linear scale of ~ 5 kpc along the arm and have a strength of -4.4 ± 0.9 μG. The magnetic field between the Carina-Sagittarius and Crux-Scutum arms is confirmed to be coherent from $l \sim 45°$ to $l \sim 305°$ over a length of ~ 10 kpc. These results strengthen arguments for a bisymmetric spiral model for the field configuration in the Galactic disk.

Subject headings: ISM: magnetic fields — pulsars: general — Galaxy: structure

1. INTRODUCTION

The origin of galactic magnetic fields is a long-debated issue, which relies heavily on good observational descriptions of the structure and strength of magnetic fields in a galaxy (Zweibel & Heiles 1997; Kronberg 1994). The current magnetic field configuration could be the result of a frozen-in primordial field in a protogalactic gas cloud which was strengthened during the collapse and formation of a galaxy (e.g., Kulsrud 1990). The strength of the primordial field should be $\sim 10^{-9}$ G to give the typical field strength (a few μG) presently seen in galaxies. A field of primordial origin would have many reversals of field direction in the galactic disk. However, the presently favored model for the field origin is dynamo amplification of a seed field by the inductive effects of the fluid motions of the interstellar medium (e.g., Ruzmaikin et al. 1988). Seed fields of at least 10^{-13} G are required. Computer simulations of dynamo action in galaxies, although far from mature, show a variety of field structures depending on the initial conditions and the details of the dynamics of medium. Usually the fastest-growing mode is axisymmetric in configuration (Ferrière & Schmitt 2000).

In the last two decades, polarization observations of synchrotron emission at centimeter wavelengths have revealed that in nearby galaxies the intrinsic magnetic field "vectors", i.e. $\mathbf{E}$+90° $\leftrightarrow$ $\mathbf{B}$ with Faraday rotation corrected, are impressively aligned along the optical arms (Beck et al. 1996; Beck 2000). Such polarization can arise not only from the regular large-scale magnetic fields as conventionally believed but also from an anisotropy in random fields (Laing 2002), for example, compressed in one dimension by a density wave shock in spiral galaxies. Evidence for coherence of field *directions*, that is, including the sense of the field, over large scales in the disks of external galaxies is fairly weak at present (e.g. Han et al. 1999a). In our Galaxy, however, rotation measures (RMs) for pulsars and extragalactic radio sources have revealed large-scale ordering of magnetic field directions in the Galactic disk, with several reversals between or within the spiral arms (e.g. Simard-Normandin & Kronberg 1980; Rand & Lyne 1994; Han et al. 1999b). Determination of the form of such directional coherence is crucially important for studies of the origin of galactic magnetic fields. Field reversals could be preserved from seed fields or there could be a mixture of dynamo modes generating the field.

Pulsar RM data suggest that the pitch angle of the local field is about –8° and its strength is about 1.5 μG (Han 2001). Between the Perseus and the Carina-Sagittarius arms the field direction is clockwise if viewed from the North Galactic pole[7], as illustated by thick arrows in Fig. 1. In the outer Galaxy, Lyne & Smith (1989), Clegg et al. (1992) and Han et al. (1999b) suggested that the direction of the regular field reverses exterior to the Perseus arm, while Canadian groups argued for no reversal between the local arm and the Perseus arm (Brown & Taylor 2001) or in the outer Galaxy (Vallée 1996). In the inner Galaxy, RMs of pulsars and extragalactic sources suggested reversed or counter-clockwise fields between the Carina-Sagittarius arm and the Crux-Scutum arm (Thomson & Nelson 1980; Simard-Normandin & Kronberg 1980; Rand & Kulkarni 1989), later confirmed by new pulsar observations (Rand & Lyne 1994). Magnetic fields beyond the Crux-Scutum arm but closer than the Norma arm *may* have a clockwise direction, as indicated by the negative RMs around $l \sim 20°$ at about 5kpc (Rand & Lyne 1994) and an RM increase at about the same distance around $l \sim 325°$.

It would be intriguing to know if the regular local fields are parts of a larger scale *coherent* field structure and if the regular fields in distant parts of the Galactic disk show reversals. Since we sit within the disk, it is not possible to have a birds-eye view of the polarized emission of our Galaxy, as for suitably oriented

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nearby galaxies (Beck et al. 1996). Analyses of starlight and Galactic background polarization data show magnetic properties only relatively locally to the Sun (e.g. Heiles 1996; Fosalba et al. 2002) or the transverse field in polarized features (Duncan et al. 1997; Uyanıker et al. 1999). Zeeman splitting of OH (or other) masers yields the line-of-sight direction and magnitude of the magnetic fields only within star-forming regions (Reid & Silverstein 1990; Caswell & Vaile 1995). RMs of extragalactic radio sources are integrated along the line of sight through the entire Galactic disk, and are always affected to some extent by Faraday rotation local to the sources[8]. Pulsars do not seem to have such intrinisic RM contributions. Moreover, pulsars cover a range of distances and therefore offer the best opportunity to investigate the 3-dimensional structure of the interstellar magnetic field over a substantial fraction of the Galactic disk.

Recently, the Parkes multibeam pulsar survey (Manchester et al. 2001) has discovered more than 600 pulsars, many of which are widely distributed over more than half of the Galactic disk. This sample therefore provides a unique opportunity for investigation of the magnetic field structure in the inner Galaxy. We have observed about 240 southern pulsars with the Parkes 64-m telescope of the Australia Telescope National Facility and obtained 202 new and improved RMs. Based on these data, we report the first firm detection of counterclockwise magnetic fields in the Norma spiral arm. A more comprehensive analysis of the full data-set will be published in a future paper.

2. PULSAR OBSERVATIONS AND ROTATION MEASURES

Pulsar polarization observations were made in two observation sessions, 1999 December 12 – 17 and 2000 December 14 – 19, using the Parkes 64-m telescope with the central beam of the multibeam receiver (Staveley-Smith et al. 1996) which is sensitive to orthogonal linear polarizations. Bands centered on 1318.5 MHz with a bandwidth of 128 MHz were processed in the Caltech correlator (Navarro 1994), which gives 128 lags in each of four polarization channels and folds the data synchronously with the pulsar period with up to 1024 bins per pulsar period. The data were transformed to the frequency domain, calibrated and dedispersed to form between 8 and 64 frequency sub-bands, with the number depending on the pulsar dispersion measure (DM), in each of the four Stokes parameters (I,Q,U,V), and corrected for variations in parallactic angle and ionospheric Faraday rotation. Because of reduced gain near the band edges, about a quarter of the bandwidth (mostly at the lower end) was abandoned, making an effective bandwidth of about 90 MHz. To reduce residual instrumental effects such as feed cross-coupling, observations of each pulsar were made in pairs with the receiver rotated to orthogonal feed angles of -45° and $+45^\circ$.

In off-line analysis, we summed the sub-band data over a set of trial RMs, searching for a peak in the linearly polarized intensity $L = (Q^2+U^2)^{1/2}$. Normally, a range of at least ± 2000 rad m^{-2} was searched with a step of about 20 rad m^{-2}. The sub-band data were then summed with the RM at which the most significant peak was found, to form two sets of Stokes profiles for the upper and lower halves of the available bandpass. A final value for the RM and its uncertainty were then determined from weighted position-angle differences across the pulse profiles. We obtained a total of 202 RMs in two sessions. Comparing the RM values of 11 pulsars with independent measurements by Costa et al. (1991) and van Ommen et al. (1997), we found that our results are consistent with and generally have better precision than previous values.

To study the magnetic field in the Galactic disk we consider only pulsars with $|b| < 8^\circ$. There are now 357 such pulsars with measured RMs, 170 of which are new measurements. The new negative RMs at direction around $l \sim 310^\circ$ and distance of 7 kpc confirm the continuity of counterclockwise fields between the Carina-Sagittarius and Crux-Scutum arms, which was originally suggested by the dominant positive RMs in the area between the two arms in the first quadrant (see Fig. 1). The fields are therefore coherent over a scale of 10 kpc along the arm. The RM data in the region $325^\circ < l < 25^\circ$, together with previously published values, enable us to identify clearly and to measure the regular magnetic field in the vicinity of the Norma arm, which we will discuss in detail below.

The mean line-of-sight component of the magnetic field (in μG) along the path to the pulsar, weighted by the local electron density, is given by

$$\langle B_{||} \rangle = 1.232\ \mathrm{RM}/\mathrm{DM} \tag{1}$$

where RM is in units of rad m^{-2} and the DM is in units of cm^{-3} pc (Manchester 1974). The mean field strength between any two points at distances of $d0$ and $d1$ in a given direction can be found from the *gradient* of the RM

$$\langle B_{||} \rangle_{d1-d0} = 1.232\ \frac{\Delta \mathrm{RM}}{\Delta \mathrm{DM}} \tag{2}$$

where $\Delta\mathrm{RM} = \mathrm{RM}_{d1} - \mathrm{RM}_{d0}$ and $\Delta\mathrm{DM} = \mathrm{DM}_{d1} - \mathrm{DM}_{d0}$. Of course, in practice, it is not possible to have sources at different distances along exactly the same line of sight, so that sources within a small area on the sky, typically a few degrees across, are taken to represent the column in that direction.

This method of using RM gradients was used first by Lyne & Smith (1989) and Clegg et al. (1992) to show the field reversals near the Perseus arm using RM data for pulsars and extragalactic radio sources. Later, Rand & Lyne (1994) and Han et al. (1999b) used it to show the field reversal near the Carina-Sagittarius arm and near the Crux-Scutum arm. The RM effects of local bubbles which are tens of degrees across (see Vallée 1984) have no effect on the differential analysis for more distant regions.

In Fig. 2 we plot the RM against DM for pulsars having RM uncertainties of < 50 rad m^{-2} and lying within 3° of six lines of sight which cross or are tangential to the Norma spiral arm. It is very clear that for DMs greater than ~ 300 cm^{-3} pc, the pulsar RMs are systematically decreasing in the longitude range of $l \sim 325^\circ$ to 350° and increasing in the range of $l \sim 10^\circ$ to 25°. We have used both the more detailed electron density model of Taylor & Cordes (1993) and the simple axisymmetric model of Gómez et al. (2001) to estimate the pulsar distances from dispersion measure values. Both models suggest that these pulsars are either associated with or beyond the Norma arm, although with a distance uncertainty of about 20% in general. Since the simple model is almost unconstrained interior to a Galactocentric radius (R) of 4 kpc, we have plotted pulsars in Fig. 1 using distances given by the model of Taylor & Cordes (1993).

The strength of the regular fields can be estimated directly from the gradient of the RM versus DM variations (Equation 2). We fitted straight lines using a least-squares procedure to the RM versus DM data for pulsars with 300 cm^{-3} pc $<$ DM $<$

[8] The RM arising within extragalactic radio sources can be more than 100 rad m^{-2}, as shown by the RMs of sources (Simard-Normandin et al. 1981) near the two Galactic poles ($|b| > 70^\circ$) where the Galactic RM contribution is only $\sim$ (+–)3 rad m^{-2} (see Sect.3.3 in Han et al. 1999b).

700 cm^{-3} pc in the longitude range of $l \sim 325°$ to 350°, and DM > 400 cm^{-3} pc in the range of $l \sim 10°$ to 25°. These DM ranges correspond to pulsars which lie in the vicinity of the Norma arm. In directions toward l = 340°, pulsars with DM in the range 200 – 300 cm^{-3} pc were also fitted, giving information on the field between the Crux and Norma arms. The results are shown Fig. 2. Pulsars around $l \sim 335°$ show the strongest evidence for a systematic field within or inside the Norma arm with an average field strength of $-4.4 \pm 0.9\mu$G. Data in other panels of Fig. 2 support or are consistent with this result. These fits are also shown as vectors in Fig. 1, where an azimuthal configuration for the field has been assumed.

The derived field strength is two or three times greater than the local regular fields (Han & Qiao 1994; Indrani & Deshpande 1998). Since the 'vertical' and 'radial' components of the large-scale field are about an order of magnitude weaker that the azimuthal component (Han & Qiao 1994; Han et al. 1999b), this is good evidence for a large-scale counterclockwise magnetic field in and interior to the Norma arm, with directional coherence over at least 5 kpc along the arm. Based on the RM data in the Galactic longitude range $320° < l < 335°$, this counterclockwise field may extend over more than 2 kpc in Galactocentric radius, roughly in the range 4 – 6 kpc.

3. DISCUSSION

The directions of large-scale regular fields in the Norma region shown in Fig. 1 clearly reveal for the first time the counterclockwise large-scale field within and interior to the Norma spiral arm. Extragalactic radio sources between longitudes of 325° to 330° have large negative RMs (Gaensler et al. 2001), consistent with a regular magnetic field parallel to the line of sight near the arm tangent.

Although evidence for a clockwise field between the Crux-Scutum arm and the Norma arm is relatively weak at present, the presence of a counterclockwise field in the Norma arm indicates another reversal in the directions of large-scale azimuthal fields in the Galactic disk. Further observations in the longitude ranges $310°-325°$ and $25°-40°$ are needed to confirm the existence and extent of the clockwise field between the Crux-Scutum and Norma arms. If this is confirmed, there will be good evidence for four reversals in the azimuthal field. Present indications are that these occur within the spiral arms, although this is not yet clear.

These field reversals are consistent with the bisymmetric spiral model for the Galactic disk field (Simard-Normandin & Kronberg 1980; Sofue & Fujimoto 1983; Han & Qiao 1994; Indrani & Deshpande 1998). They appear inconsistent with the axisymmetric model of Vallée (1996), since this model does not allow any field reversal exterior to the Perseus arm or interior to the Crux-Scutum arm. The field reversals are most probably a remnant of primordial fields at the time our Galaxy formed. These act as 'seed' fields for dynamos operating in the conductive interstellar medium (Kulsrud 1999). Dynamo action is necessary to counteract diffusion of the large-scale field structure. However, we cannot exclude the possibility that such a bisymmetric field could be the result of a strong non-axisymmetric configuration of the dynamo induced, for example, by tidal interaction with the Magellanic Clouds (see Moss 1995).

It is desirable to understand why our Galaxy has several reversals in the thin Galactic disk as revealed by pulsar and extragalactic RMs, while few reversals are known in nearby galaxies. Reversals are known to exist in M51 (Berkhuijsen et al. 1997), in M81 (Krause et al. 1989b) and possibly in NGC2997 (Han et al. 1999a). Polarization observations of external galaxies alone cannot distinguish reversals in the field direction. RM maps deduced from multifrequency polarization maps generally have a lower resolution than interarm separations or field-reversal scales, and hence it is difficult to identify reversed fields (see also Heiles 1995). The polarized emission observed in nearby galaxies mainly comes from a thin disk and it indicates the orientation of regular fields or possibly the anisotropy of random fields in the disk. However, the Faraday rotation of the polarized emission, which has been used to infer the presence or absence of field reversals in nearby galaxies, may originate mainly in the intervening thick disk or halo. Even if the thin disk field has reversals, the halo field may be axisymmetric and have no reversals. For example, there is evidence that our Galaxy has an axisymmetric halo field generated by an A0 dynamo (Han et al. 1997). The mixture of axisymmetric and bisymmetric spiral fields in external galaxies (Beck 2000) may be explained if the thin disk, thick disk and halo are together responsible for the RM distribution.

The coherence of field directions in our Galaxy revealed by pulsar RMs independently show that the regular magnetic fields do indeed exist on galactic scales. Though we can not exclude that some of the linear polarization is caused by anisotropic random fields, our results show that at least some of the linear polarization arises from large-scale coherent fields. Therefore, it is likely that polarization "vectors" observed in the external galaxies (Beck et al. 1996; Beck 2000) represent the large-scale regular magnetic field.

An increase in strength of the large-scale field with decreasing Galactocentric radius is expected in both dynamo models (Ruzmaikin et al. 1988) and for fields of primordial origin (Kulsrud 1990). With a few more measurements, it will be possible to determine if the field strength obeys the relation $B \propto 1/R$, which is a critical profile for the field to affect the dynamics of the Galaxy (Battaner & Florido 2000; Kronberg 1994).

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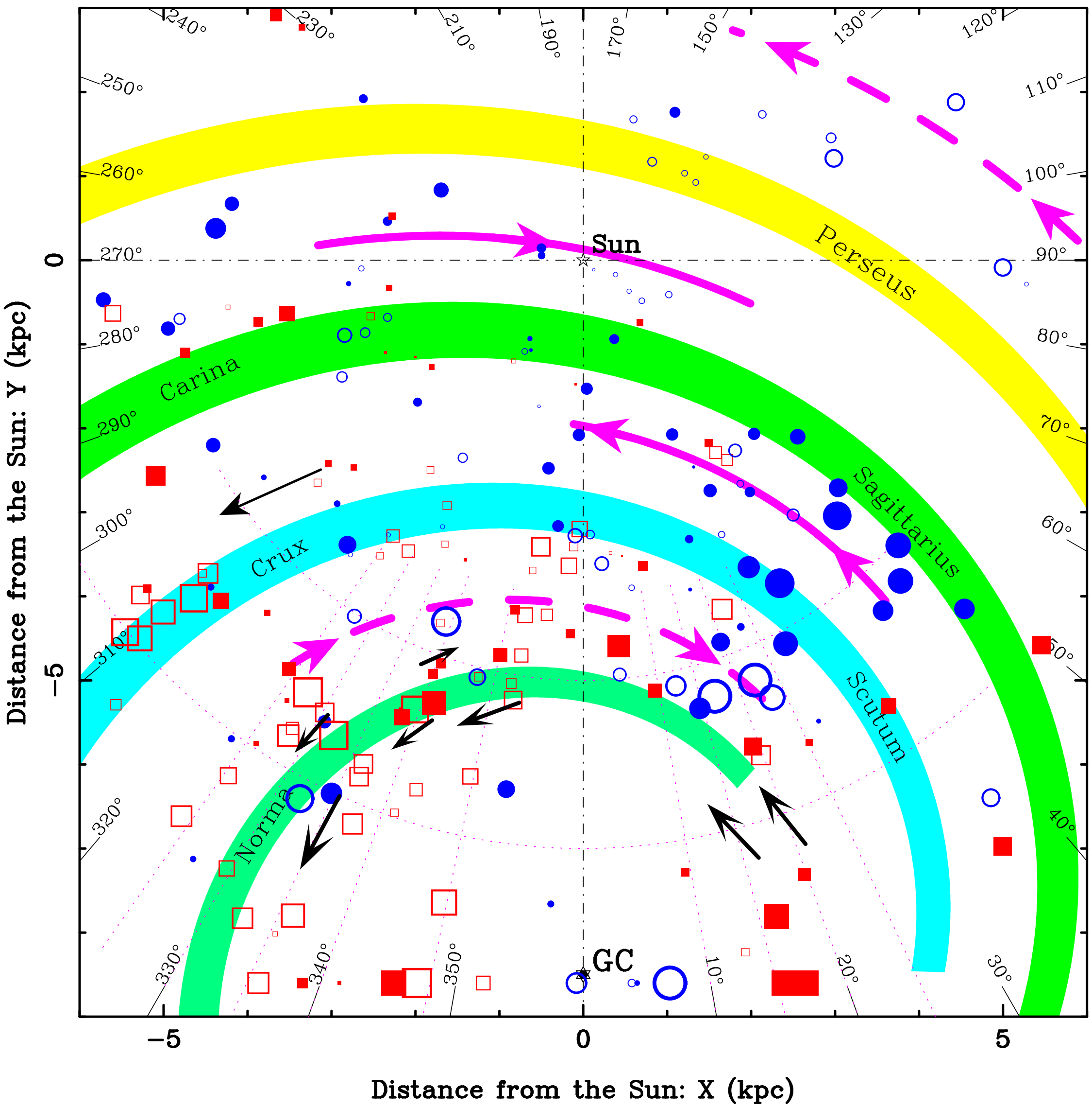

FIG. 1.— Rotation measures of pulsars having $|b| < 8°$, projected on to the Galactic Plane. The areas of the symbols are proportional to the RM magnitudes, with limits of 5 and 800 rad m^{-2}. Filled symbols represent positive RMs and open symbols indicate negative RMs. New measurements are indicated by squares. Pulsar distances were calculated by using the model of Taylor & Cordes (1993). Approximate locations of four spiral arms are indicated (Georgelin & Georgelin 1976; Downes et al. 1980; Caswell & Haynes 1987). The generally accepted magnetic field directions between the Perseus and Carina-Sagittarius arms and between Carina-Sagittarius and Crux-Scutum arms are illustrated by thick lines and arrows. Evidence exists for field directions exterior to the Perseus arm and between the Crux-Scutum and Norma arms, as shown by thick dashed lines and arrows (see text), but more data are needed to confirm them. Field directions near the Norma arm are plotted according to fitted pulsar RM gradients as shown in Fig.2. Dotted lines indicate distances of 5 and 7 kpc from the Sun and some Galactic longitudes of interest.

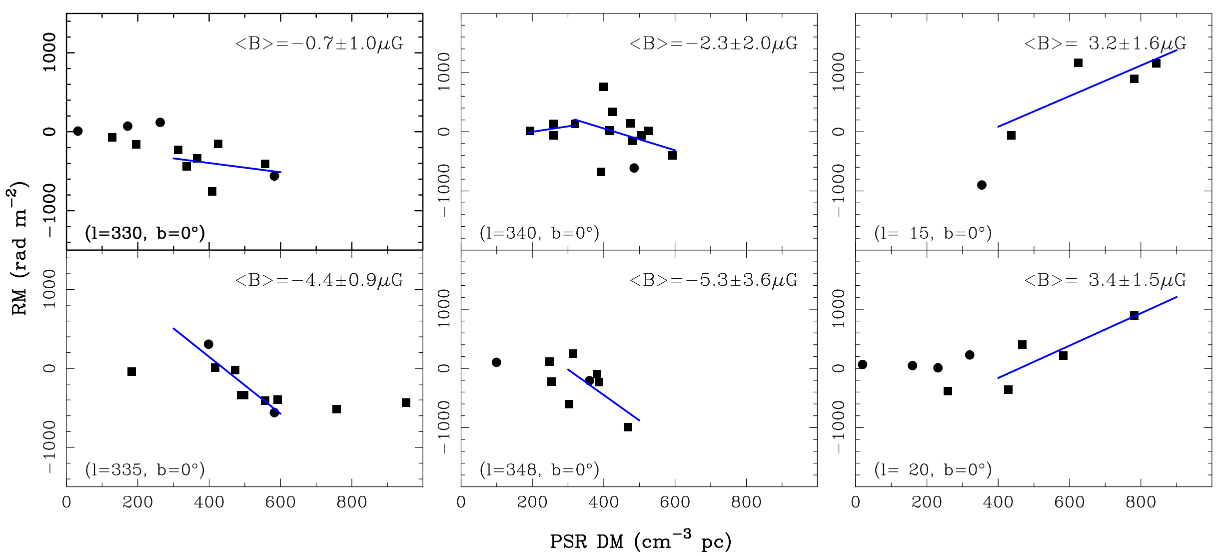

FIG. 2.— Variations of RM versus DM for pulsars within 3° of six lines of sight passing near to or across the Norma arm. New RM measurements are indicated by squares. Straight-line fits to the data near the Norma arm are indicated by the lines in each panel. Toward $l = 340°$, we also fit closer pulsars giving information on the field between the Crux and Norma arms.